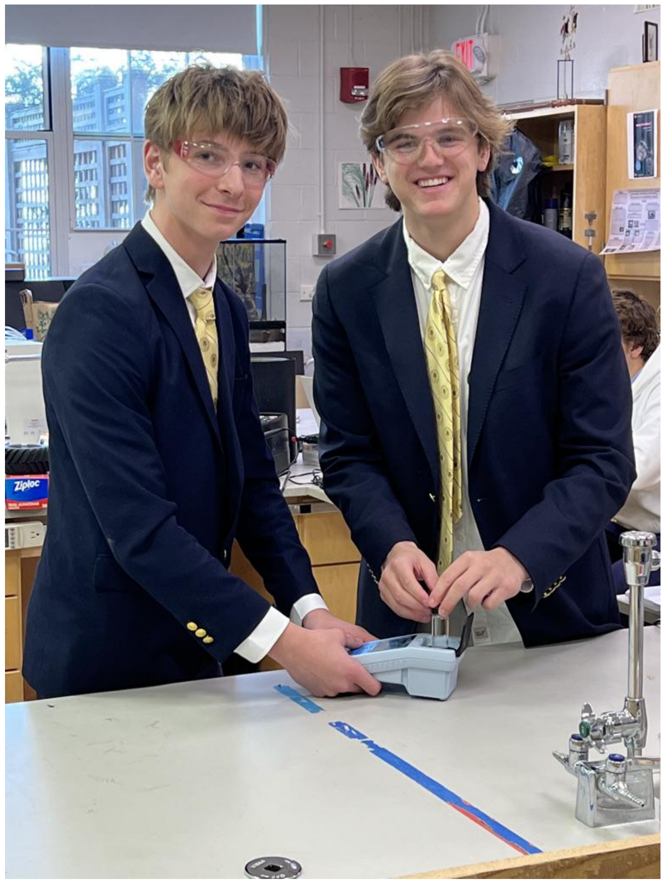
A Comparative Analysis of Thermal, Solar, and Membrane Desalination



March 2022

Project Number 6501

Abstract

The objective of this project was a comparative analysis of various desalination methods including membrane, thermal, and solar desalination. All three methods have their own advantages and disadvantages, and this study sought to compile a comprehensive data set for use in identifying the most efficient method for specific situations, especially as the world moves toward more frequent usage of desalination. The proficiency of each method was investigated using variables such as the extent of pretreatment required, initial water quality, and time efficiency. The independent variables included energy required, resulting water quality, and risk to the environment. Brackish water from the Long Island Sound was combined with sea salt and soil to standardize the initial water quality. Each method was successful in desalinating the starting 1 gallon of water to a potable range of turbidity and pH as well as a 0.0 ppt salinity. Thermal distillation resulted in the lowest turbidity and most ideal pH but was not very time or energy efficient. Solar distillation has the advantage of requiring no energy input and resulted in only slightly worse pH and turbidity as compared to thermal distillation however it's inefficiency in terms of time rendered it impractical for use on a small scale. Membrane desalination was extremely quick and used a minimal amount of energy as compared to thermal distillation however the resulting water was significantly more basic compared to the other two techniques and the turbidities were slightly higher as well.

Introduction

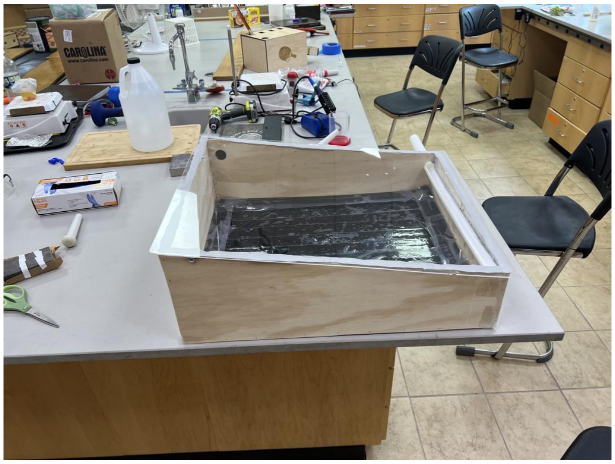
Water is now and always has been the source of all life on earth. Water is necessary to sustain human life. As such, the search for clean drinking water has been a focus of human civilization for several millennia. However, only 2.5% of all water on earth is freshwater according to National Geographic. In addition, the vast majority of this water is not available to be extracted and used. All in all, only .007% of the planet's water is available for use. This scarcity of drinking water, however, is somewhat made up for by the abundance of saltwater on our planet with 97.5% of all water on earth being salt water. This abundance has led many of the nations of the world, especially those in dry climates or those who lack access to freshwater, to turn to desalination in an attempt to use our seemingly endless supply of salt water to hydrate their populations. Earliest attempts at desalination included harnessing the power of the sun to evaporate salt water which could then be later condensed into pure drinking water. Then humans attempted to recreate this process but replaced the sun with fire and electrical heat in an attempt to standardize the process. More recent desalination methods have included pressurizing the salt water to force it through extremely small holes in a semi-permeable membrane. Each of these methods has their own strengths and weaknesses and none are practical for universal application. For example, modern membrane desalination plants are extremely quick and can churn out large amounts of water each day but are extremely expensive to run and maintain. As the world moves towards a more frequent usage of desalination it is important to get a grasp of these strengths and weaknesses. For this reason we sought to collect data on the proficiency of each method in terms of energy and time efficiency and resulting water quality at differing levels of pretreatment.

Importance of Turbidity, pH, and Salinity

Turbidity measures the amount of particles in a sample of water in Nephelometric Turbidity Units or NTU. Turbidity is caused by chemical and biological particles in water and is a measure of both safety and aesthetic. It is measured on a scale of 0-800. A water with a Turbidity of 0 would have no excess particles within it and the WHO recommends water to be below 5 NTU with the ideal level being below 1 NTU. Turbidity indicates pathogens and other dangerous particles within water. In water with higher turbidity, pathogens are more likely to be found as particles can often host microorganisms. pH is also another measurement needed for determining whether water is potable. pH shows water solubility as well as resources for aquatic organisms. Solubility is important as it can reveal the toxicity of water regarding metals such as lead and copper. Metals in water at a lower pH are more toxic, because the water is more soluble. The pH levels must be between 6.5 - 8.5 for the water to be considered potable with 7.0 being considered the perfect pH level. Salinity is the last measurement we used which measures how much salt is in the water in parts per thousand (ppt).

Purpose/Objective

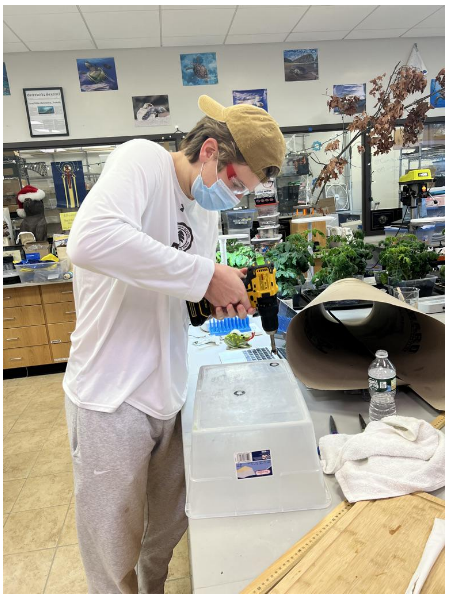
The purpose of this study was to compile a comprehensive data set for the three most prevalent methods of desalination: solar, thermal, and membrane. The data set would include time and energy efficiency, resulting water quality in terms of pH, salinity, and turbidity, and proficiency at different degrees of pretreatment. Using this data, the correct desalination technique could be more easily identified for varying situations. It was hypothesized that due to the two step process of evaporation and condensation, thermal and solar desalination would result in the most pure water. However, it was also hypothesized that solar would be the least efficient in terms of time and that thermal would be the least efficient in terms of energy usage. In comparison, membrane desalination was hypothesized to be very efficient in terms of both time and energy yet less effective in the purification of the water due to some impurities making it through the membrane.



Materials/Methodology

Stage One: Gathering Materials and Setting up Experiments

For solar desalination, a solar still was built from scratch in the lab using plywood, rigid insulation, plexiglass, a PEX pipe, and weather sealant tape. First, the plywood was cut to size and then nailed together to form the frame of the still. Then, the bottom of the still was covered in rigid insulation with a layer of weather sealant tape on top of that. Two holes were then drilled into one of the sides of the still. One hole was to act as an inlet for inputting our water and the other was to be filled with the 1 inch diameter PEX pipe for outputting the water. The PEX pipe was glued to the low end of the still using caulk placed at a 9 degree angle, and the top was cut off, allowing for the output water to flow out of the still. Lastly, we caulked the plexiglass on top and covered the edges of the box in weather sealant tape. For thermal desalination, a stainless steel still pot was ordered. This still pot was connected to a tubing system which circulated cold water in order to aid in the condensation of the pure water. This system was then placed on top of a hot plate capable of reaching 550 degrees celsius. Lastly, a voltage tester was placed on the outlet of the hot plate to determine how much energy the hot plate was consuming. For membrane desalination, we ordered a RO membrane filter which filters nearly all particulate matter and combined that with an activated carbon filter which filters the organic matter in the water which the RO membrane struggles with. Brackish water was collected from the Long Island Sound to be used in all tests and was standardized at three different levels of pretreatment. We standardized water at 50, 100, and 200 NTU turbidity and recorded the salinity and pH for each.



Stage Two: Testing

For thermal desalination, the hot plate was allowed to heat up to 550 degrees celsius for 30 minutes before being plugged into the voltage tester. The still pot was then filled with the standardized starting water and placed on top of the hot plate. The water inside the pot would be vaporized by the heat from the hot plate and converted into steam. This steam made its way up into the condensing portion of the system where the circulating cold water would cool the water down and condense it, at which point it could flow out of an output tube and into a collecting container. For solar desalination, first the water was added to the solar still using the

input hole drilled into the side of the still. The input hole was then plugged up and an infrared heat lamp was set up directly above the glass ceiling of the still. The heat from the

heat lamp vaporized the water inside the still. The steam from this water rose to the top of the still where it condensed along the glass ceiling. These newly condensed water droplets then made their way down the glass which was sloped at a 9 degree angle and into the PEX pipe. The water then followed the PEX pipe out of the still and into a collecting container. For membrane desalination, the standardized initial water was first shot through the activated carbon filter in order to remove any large particulate matter as well as any organic matter. The resulting water was then collected and similarly forced through the reverse osmosis membrane which removed nearly all remaining impurities. Calculations involving the weight and pressure of the input water were used to determine the energy usage of membrane desalination. Each of these three methods were tested using one gallon of water at 50, 100, and 200 NTU. Three tests were completed at each of the three turbidities for each desalination method, with a total of 27 tests run. After each technique had desalinated the water, the water was tested for a final turbidity, pH, and salinity.

Results

Thermal Desalination:

	Starting Salinity(PPT)	End Salinity(PPT)	Starting pH	End pH	Time	Final Turbidity(NTU)	Energy (kwh)
50 NTU Trial 1	21.3	0	7.44	7.04	6:02	0.37	3.78
50 NTU Trial 2	21.3	0	7.44	7.04	6:01	0.39	3.61
50 NTU Trial 3	21.3	0	7.44	7.02	5:44	0.33	3.77
100 NTU Trial 1	27	0	7.51	7.06	5:57	0.42	4.03
100 NTU Trial 2	27	0	7.51	7.09	6:18	0.49	3.86
100 NTU Trial 3	27	0	7.51	7.05	5:59	0.39	3.84
200 NTU	30.9	0	7.63	7.09	6:12	0.57	3.71

Trial 3							
200 NTU Trial 3	30.9	0	7.63	7.18	6:03	0.54	3.91
200 NTU Trial 3	30.9	0	7.63	7.12	6:02	0.46	3.97

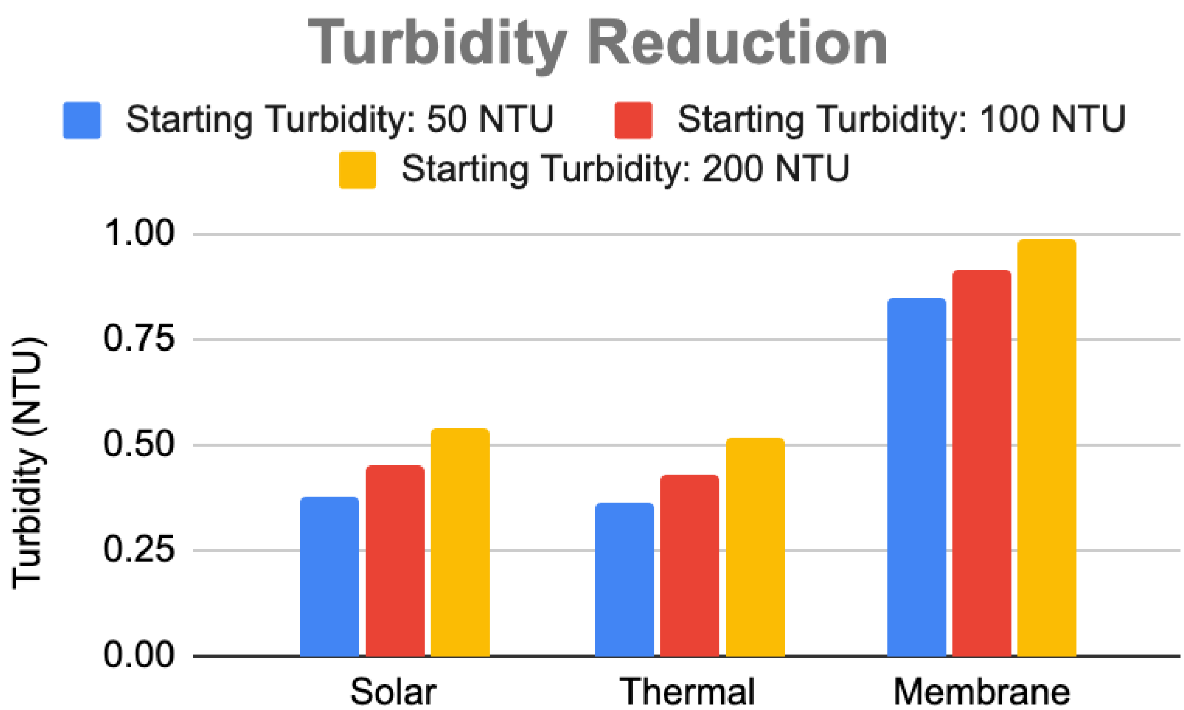
Solar Desalination:

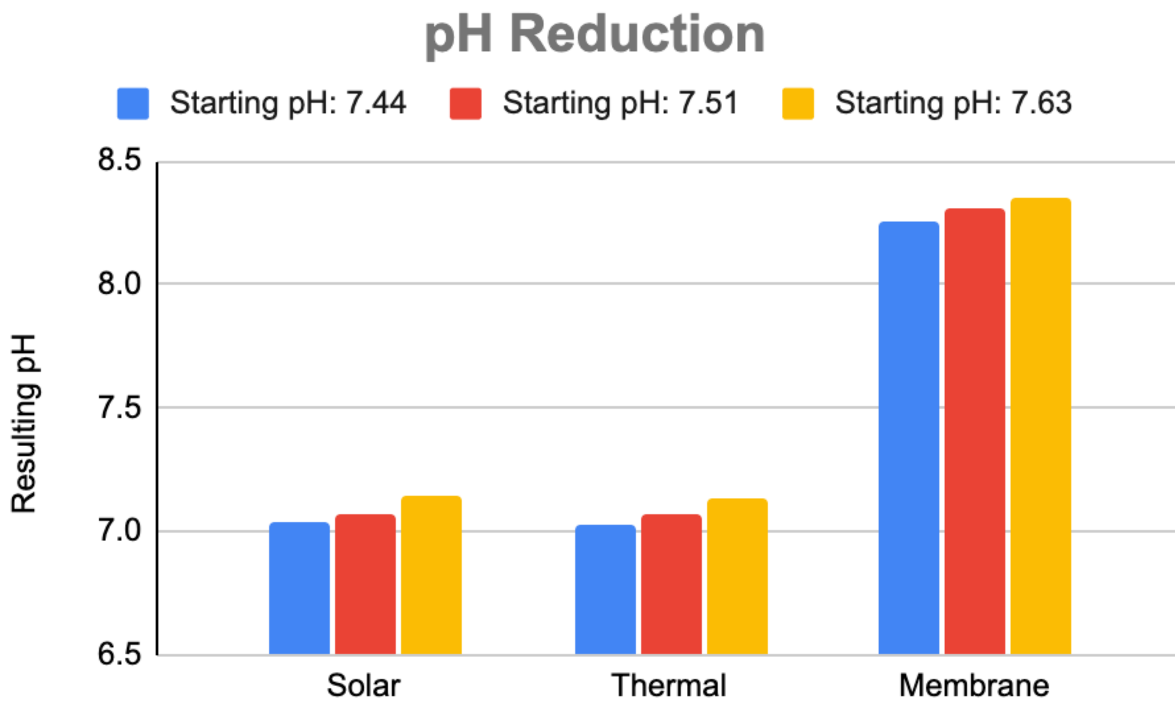
50 NTU Trial 1	21.3	0	7.44	7.04	~	0.36	0
50 NTU Trial 2	21.3	0	7.44	7.02	~	0.4	0
50 NTU Trial 3	21.3	0	7.44	7.06	~	0.38	0
100 NTU Trial 1	27	0	7.51	7.06	~	0.41	0
100 NTU Trial 2	27	0	7.51	7.1	~	0.47	0
100 NTU Trial 3	27	0	7.51	7.05	~	0.47	0
200 NTU Trial 1	30.9	0	7.63	7.09	~	0.53	0
200 NTU Trial 2	30.9	0	7.63	7.16	~	0.51	0
200 NTU Trial 3	30.9	0	7.63	7.17	~	0.58	0

Membrane Desalination:

50 NTU Trial 1	21.3	0	7.44	8.25	6:52	0.84	0.000436
50 NTU Trial 2	21.3	0	7.44	8.24	7:43	0.88	0.000436
50 NTU Trial 3	21.3	0	7.44	8.29	7:10	0.83	0.000436
100 NTU Trial 1	27	0	7.51	8.33	7:57	0.89	0.000436
100 NTU Trial 2	27	0	7.51	8.31	6:56	0.92	0.000436
100 NTU	27	0	7.51	8.29	7:27	0.93	0.000436

Trial 3							
200 NTU Trial 1	30.9	0	7.63	8.32	7:44	0.96	0.000436
200 NTU Trial 2	30.9	0	7.63	8.42	7:49	1.04	0.000436
200 NTU Trial 3	30.9	0	7.63	8.31	7:34	0.99	0.000436





Discussion

Each of our 27 tests was successful in desalinating the starting water from each of the three initial standards to below the acceptable range of turbidity for drinking water of 5 NTU and all but one below the ideal range of 1 NTU. In addition, all tests successfully resulted in water within the potable range of pH from 6.5 to 8.5 and a 0.0 ppt salinity. The exact results, however, varied from method to method. Thermal desalination resulted in the purest water, slightly edging out solar desalination. It desalinated the 50 NTU water to an average of .36 NTU, 100 NTU to .43 NTU, and 200 NTU to .52 for an average turbidity reduction of 99.53%. Additionally, thermal desalination was able to desalinate from 7.63 pH to an average of 7.03, 7.51 to 7.07, and 7.63 to 7.13 for average reductions of 93.18%, 86.27%, and 79.37% respectively about the ideal pH for drinking water, 7.00. This drop in percentage at higher initial pH represents a drop in efficiency of thermal desalination at lower levels of pretreatment in terms of pH. Despite its proficiency in terms of water quality, thermal desalination proved itself inefficient in terms of both time and energy. The tests took an average of 6 hours and 2 minutes to desalinate the 1 gallon of starting water, significantly slower as compared to membrane desalination. In terms of energy, the tests consumed an average of 3.83 kwh, exponentially higher energy consumption than either membrane or solar desalination. These high energies and times may be due in part to certain inefficiencies in our thermal desalination system.

Solar desalination was second most proficient in terms of resulting water quality, falling just behind thermal in nearly every test. It desalinated 50 NTU to an average of .38 NTU, 100 NTU to .45 NTU, and 200 NTU to .54 NTU for an average turbidity reduction of 99.51%. pH wise, it desalinated the 7.44 pH initial water to an average of 7.04, 7.51 to 7.07, and 7.63 to 7.14 for average reductions of 90.91%, 86.27%, and 77.78% respectively about 7.00 pH. These pHs are all slightly higher than those of thermal desalination and show a similar trend of a decrease in efficiency at higher initial standards. The slight increase in impurities from thermal to solar is slightly puzzling because they both involve the same evaporation, condensation process. However, the newly condensed water in our solar still must make its way down the plexiglass and then the PEX pipe before being collected which could have added trace amounts of extra particulate matter. Solar obviously consumed zero energy, seeing as the heat for the reaction is provided by the sun. However, solar desalination was extremely impractical in terms of time efficiency. With the amount of time we had to complete our study, the time results for solar desalination had to be scrapped as from early estimates it could take more than a day to fully desalinate each gallon of water. This may be due to inconsistencies in the heat being produced by the heat lamp or heat not making it through the plexiglass ceiling of the still.

Membrane desalination was slightly less proficient in terms of the purity of the produced water as compared to solar and thermal desalination. It desalinated the initial 50 NTU water to an average turbidity of .85 NTU, 100 NTU to .91 NTU, and 200 NTU to .99 NTU for an average reduction of 98.96%. These turbidities may be higher as compared to the other two techniques due to a relatively larger amount of impurities being able to make it through the reverse osmosis membrane filter as compared to those which were able to stick with the water as it evaporated and condensed in the thermal and solar desalination tests. In terms of pH, membrane desalination resulted in significantly more basic water than the other two methods. It desalinated the water with an initial standard of 7.44 pH to an average of 8.26 pH, 7.51 to 8.31 and 7.63 to 8.35. Not only was the resulting water significantly more basic using membrane desalination, the process actually increased the pH by an average of 10.37%. This increase in basicness most likely resulted from the activated carbon filter which was used in tandem with the reverse osmosis membrane. Activated carbon is a basic substance with a pH of typically 9.5-10.5 and as such most likely increased the pH of the water being pushed through the filter. Membrane desalination was extremely efficient in terms of both energy and time. Using calculations involving the weight and pressure of the water it was determined that our membrane desalination process would consume approximately .000436 kwh which is exponentially lower energy consumption as compared to thermal desalination. The membrane tests took an average of 7 minutes and 28 seconds to complete, significantly quicker than either solar or thermal desalination.

One possible error across all tests would be a lack of proper sanitation between tests. We did not have access to perfect cleaning materials when performing our experiments and as such some impurities may have been left behind with each completed test. This may have caused a decrease in efficiency in the later 100 and then 200 NTU tests and could explain the trend identified in thermal and solar where the pH reduction efficiency dropped in the later tests at higher initial pHs.

These results correlated with our expectations going into the experiment as well as commonly held beliefs in terms of where each method would thrive and struggle. However, the loss of efficiency at higher turbidities in terms of pH reduction as well as the high pH of the membrane desalinated water were unexpected.

If we were to repeat this experiment we would probably work on a much larger scale. In the world, desalination mostly takes place at large plants which churn out thousands of gallons per day. This larger scale could have significant effects on the efficiency of each method. In addition, we would like to experiment with some of the more contemporary, emerging methods of desalination including: electrodialysis, nano-filtration, and multi-stage flash distillation. These newer, more advanced methods are the ones which are going to be realistically used in the future to fill our desalination needs so it is important to gather data and learn more about them.

Conclusion

Solar desalination was found to be the most sustainable method of desalination due to the fact that it requires no energy input. Additionally, solar produced extremely pure water. Despite these obvious strengths, in our small scale experiment, time proved a devastating issue. Solar desalination could be a strong candidate for future desalination if used on a much larger scale which could possibly improve its time efficiency. Thermal desalination was also extremely proficient in purifying the water but its high energy usage makes it impractical for use unless the energy efficiency of the process can be improved. Membrane desalination is probably the strongest candidate for use in future desalination due to its efficiency in terms of both energy and time. Although the resulting water did contain more impurities as compared to the other two methods, we believe this could be easily mitigated by pushing the water through the membrane multiple times or through a tighter membrane.

References

1. Bienkowski , Brian. "Desalination Is an Expensive Energy Hog, but Improvements Are on the Way." Advances Coming in Desalination Technology, Ensia , 15 May 2015, https://www.pri.org/stories/2015-05-15/desalination-expensive-energy-hog-improvements-are-way
2. California-Great Basin, Bureau of Reclamation. "Central California Area Office." Water Facts - Worldwide Water Supply | ARWEC| CCAO | Area Offices | California-Great Basin | Bureau of Reclamation, 4 Nov. 2020, https://www.usbr.gov/mp/arwec/water-facts-ww-water-sup.html#:~:text=2.5%25%20of%20the%20earth's%20fresh,water%20is%20available%20fresh%20water.
3. Chandler , David L. "Turning Desalination Waste into a Useful Resource." MIT News | Massachusetts Institute of Technology, 19 Feb. 2019, https://news.mit.edu/2019/brine-desalianation-waste-sodium-hydroxide-0213.
4. Communications, ClientEarth. "Fossil Fuels and Climate Change: The Facts." *ClientEarth*, 11 Nov. 2020, https://www.clientearth.org/latest/latest-updates/stories/fossil-fuels-and-climate-change-the-facts/#:~:text=The%20Intergovernmental%20Panel%20on%20Climate,from%20fossil%20fuels%20and%20industry.
5. "Desalination Completed." *Desalination | U.S. Geological Survey*, https://www.usgs.gov/special-topics/water-science-school/science/desalination.
6. Eittreim, S., et al. "Turbidity Distribution in the Atlantic Ocean." *Deep-Sea Research and Oceanographic Abstracts*, 1 Jan. 1976, https://pubs.er.usgs.gov/publication/70011148#:~:text=The%20bottom%20waters%20of%20the,is%20in%20the%20equatorial%20regions.

7. Kumar, A., Phillips, K.R., Thiel, G.P. et al. Direct electrosynthesis of sodium hydroxide and hydrochloric acid from brine streams. Nat Catal 2, 106–113 (2019). https://doi.org/10.1038/s41929-018-0218-y
8. Ledesma , Lilian. "Desalination: The Solution to Our Problems?" Heal The Bay , 1 July 2015
https://healthebay.org/sites/default/files/Desalination%20FAQ%20Sheet_final.pdf. San Diego Country , Water Authority. "Seawater Desalination." San Diego County Water Authority, 28 Dec. 2020, https://www.sdcwa.org/your-water/local-water-supplies/seawater-desalination/.
9. Masterson, Victoria. "'Renewables' Power Ahead to Become the World's Cheapest Source of Energy in 2020." *World Economic Forum*, https://www.weforum.org/agenda/2021/07/renewables-cheapest-energy-source/.
10. Rogers, Paul. "Nation's Largest Ocean Desalination Plant Goes up near San Diego; Future of the California Coast?" *The Mercury News*, The Mercury News, 23 Jan. 2017, https://www.mercurynews.com/2014/05/29/nations-largest-ocean-desalination-plant-goes-up-near-san-diego-future-of-the-california-coast/#:~:text=Desalinated%20water%20typically%20costs%20about,state%20Department%20of%20Water%20Resources.
11. San Diego Country , Water Authority. "Seawater Desalination." San Diego County Water Authority, 28 Dec. 2020, https://www.sdcwa.org/your-water/local-water-supplies/seawater-desalination/.
12. Terra Mater, "How to Turn Sea Water Into Fresh Water Without Pollution." *YouTube*, YouTube, 9 Apr. 2021, https://www.youtube.com/watch?v=KdFIHecZDfc. Accessed 28 Oct. 2021.
13. "The Cost of Desalination." *Advisian*, https://www.advisian.com/en/global-perspectives/the-cost-of-desalination#:~:text=3.1%20Desalination%20technology,et%20al.%2C%202012).